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INTRODUCTORY REVIEW OF UNDERWATER ACOUSTIC PROPAGATION AND ITS MODELLING

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ABSTRACT

Underwater acoustic propagation modelling has to cope with a great variety of paths and regimes, with somewhat different sets for deep water, shallow water, and range-dependent conditions. There is also a great variety of theoretical approaches for these different paths and for the different frequencies. The necessary comparison with the real world brings further problems, due especially to lack of good environmental information and to variability. Brief mention must also be made of the customers and the applications, as well as the accuracy desirable and that attainable.

INTRODUCTION

Why should there by any need for a tutorial session on underwater acoustic propagation? First, because it is important, and underlies the design and performance of all underwater acoustic systems. Second, because we meet a very great variety of propagation conditions, as will be demonstrated.

Third, for a given condition, it can be surprisingly complicated. Thus figure 1 shows a ray trace in a surface duct, a region in which there is merely a constant positive gradient of sound velocity assumed down to the duct bottom, and in which we obtain a complex set of caustics and shadow zones (Ref 1). Figure 2 is for a duct with a parabolic profile, giving us another interesting pattern, but one differing from the first one in all its characteristics. It may be objected that we did not start with isovelocity water, such as may be encountered in shallow water, and where indeed the ray trace is rather dull. But we can cheat and look for this case at the parabolic-equation (PE) contoured plot of transmission loss in Figure 3, which takes account of the wave nature of the propagation, and shows sets of apparent beams as well as major focal points.

Following on we note, fourth, that is is rarely easy to model all this theoretically. And, fifth, nothing is still in the real world and we have omnipresent fluctuation.

There is much to introduce and the writer asks forgiveness for using a few lists: these can always be admired but left unread. He also believes in not leaving unsaid some of the more obvious and simple things, claiming that these really hide much sophistication.

There are many excellent books which include information on propagation underwater, but in citings Refs 2-8 we pick on textbooks and long reviews which concentrate on this subject.

THE MEDIUM

Typically we may wish to look at frequencies between 25Hz and 2.5 kHz, depths down to the deepest existing, and ranges to say 200 km. But it would not be unusual to cover more extreme frequencies or greater ranges. We need to be interested in the water profiles of velocity and attenuation; the bottom topography, structure, attenuation etc; and the sea surface roughness. One modern technique that can help in collecting environmental data is remote sensing by aircraft or satellite. Of course this may also be used to look at the land and everyone knows of the diversity of landscape that exists- consider now that a similar diversity occurs in the ocean!

DEEP-SEA PATHS

A typical water depth in the deep sea is, say, 4000 m. The following list covers most of the acoustic paths that we may meet in the deep ocean. The profile in Figure 4 show the three velocity minima, ducts or channels.

Direct from source and surface image (Lloyd's mirror)
Reflected at the bottom
Refracted within the bottom (not at short-range)
Surface duct (mainly in winter)
Depressed or shallow sound channel (some areas)
Main sound channel
Whole deep water channel, including multiple bottom bounce paths
Convergence zone (if water deep enough)
Combination paths such as surface-duct/ convergence zone

This list is really a hybrid. It gives the impression that all the paths can co-exist, provided the geometry and the frequency range are right, and this is true in most cases. But some paths are really developments of others (eg direct and surface duct), and some are just special forms of others (eg convergence zone and main channel). We give just the one illustration in Figure 5, but see eg Ref 4.

SHALLOW-WATER PATHS

Shallow water is encountered on the Continental Shelf with a typical depth of, say, 100 m. The area of shallow water is only about 10% of that of the oceans as a whole, but it is where a disproportionate amount of the action takes place and it is of comparable importance to deep water. Traditionally it has proved even more difficult to model than has deep water. Instead of a list of paths we present the plan of propagation regions in Figure 6, based on Ref 9. This split-up in shallow water is quite different to that in deep water, largely because we are dealing with much longer ranges when measured in units of water depth. Thus for a given range and frequency the different propagation regions cannot generally co-exist: we are either in a particular region or in effect passing from one into another. Thus as we move out in range we start with direct-path spherical spreading, progress to cylindrical spreading with a proportion of the energy trapped between surface and bottom, then to an intermediate spreading law in the stripping region where energy at the steeper angles is selectively attenuated. Eventually the first normal mode may be left predominant, though at higher frequencies refraction starts to bite first. Ref 9 provides simple formulae for most of these regions, which match up at the region boundaries, and there are later developments along these lines, especially in the Chinese literature.

The schematic in Figure 7 illustrates the cylindrical spreading case, with level for a unit source given by

$$F = \Phi / RH.$$

Here Φ is the included angle effective, nominally equal to twice the angle for total internal reflection at the bottom, ϕ_C , R is range and H is water depth. This formula works to a first order in most other examples of ducted propagation, with a suitable choice for Φ and H, and provides an invaluable check on fancier propagation theories and computer outputs. (We can even try it in range-dependent media by using Φ at one end of the path and H at the other end).

The bottom-path region in Figure 6 has somewhat fuzzy boundaries and can provide an exception to the rule about no co-existence. It was specified for paths refracting through the bottom, but could also be taken to cover interface waves associated with bottom rigidity.

The unexpected or novel or exciting does still happen in underwater acoustics, as exemplified in Figure 8, and in presenting it the writer reflects this characteristic as he temporarily abandons any pretence at balance in this review. The figure shows very old data (Ref 10) where it has long been realised that the reduction in level on approaching the bottom is associated with the presence of free sedimentary gas: but only lately understood that the April result is due to a zero-order mode or interface wave of a new type allowed by this gas.

RANGE-DEPENDENT PATHS

The reference here is to paths in a medium which is range-dependent as regards either topography or water structure. This can happen for any water depth but it is most important for those intermediate depths, statistically rare, which correspond to the Continental Slopes. Propagation type is liable to change along the path, eg the energy starting off in the depressed or main channel is likely eventually to undergo multiple bottom bounces as it proceeds upslope, and if changes are slow enough the adiabatic mode law will be followed (Ref 1). Any model dealing with long ranges must be able to cope with range dependence. Variations across the acoustic track can also be significant, since they produce a horizontal refraction of the path, but we are in danger of straying again into parts of the subject which are too specialised.

MODELLING APPROACHES

It is possible to construct trees showing the relations between the various theoretical methods, but here we just give a list.

Wave equation exact solution (occasionally possible, benchmark)
Wave equation solution by finite elements
Ray tracing
Normal modes

WKB approximation to modes
Fast-field programme
Marching solutions (eg parabolic equation)
Averaged or compact or simple methods (eg flux)
Empirical (this is not theory but can be a model)

The ray and parabolic equation results have already been illustrated, here we add Figure 9 for the range-averaged flux approach, which is near the writer's heart. The surface-duct structure of Figure 1 is certainly simplified, but enough remains to keep us busy.

Of course nowadays most models are computer-based, and there are commonly several named models within each category, as well as hybrids. This plethora of models presents us with a major problem in choosing, since they all have their pros and cons, and the best choice will also be highly dependent on frequency.

THE REAL WORLD

It is fashionable and it is right to wish to verify models by comparison with measurements: the writer prefers the term "calibrate". These measurements have their own techniques and their own problems, which we will not explore here The comparison itself is difficult because there is never quite enough knowledge of the environment and because the said environment varies in both space and time. The schematic in Figure 10 illustrates this last point for a shallow-water area in the Bristol Channel, with a display of 8 different mechanisms for amplitude fluctuation. It is for a few tens of km range, audio frequencies and fixed end points. The medium and long-term effects can play havoc with predictions. On mechanism b: an attenuation of 50dB has been observed due to the presence of dispersed fish at night, though this figure is exceptional. On mechanism c: a storm with winds exceeding 20m/s is strong enough to wipe out any normal signal in the kiloHerz region.

APPLICATIONS

Potential customers for modelling include-

Navies and Air Forces
Associated groups in Government and Industry
Students of the sea in Universities, Geophysical, Oceanographic and Biological Institutions
Oil Companies
Fisheries Scientists and Fishermen

The main applications lie in the predication of ranges for sonars, torpedoes, mine-hunting, mine-sweeping, communications etc. In detail these predictions may be used in operations, assessments, design, trials planning and analysis, research and education.

For most of this work the writer considers that a reasonable but arbitrary figure for the desirable modelling accuracy is ± 2dB. Bearing in mind the input uncertainties as well as the modelling this is also just about the figure that can be achieved in good conditions: the achievable accuracy can be much worse in bad conditions.

CONCLUSION

It is hoped that the flavour of the subject is beginning to emerge. In this review the writer has swung between the spreading of gloom at all the complications or obstacles, and the countervailing view that there are indeed routes through them. He leaves it to his colleagues to map these out.

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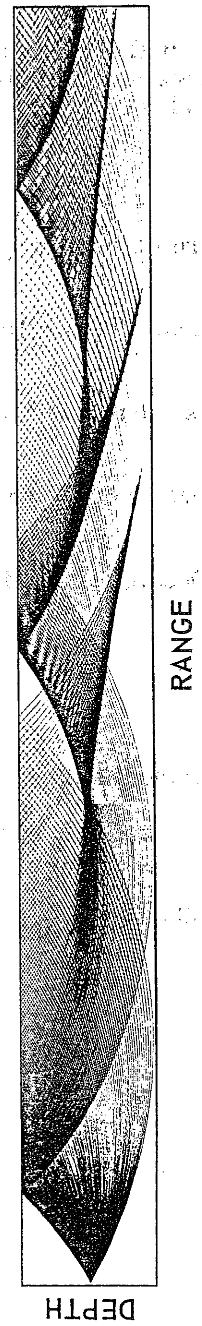

Figure 1 Ray Tracing in a Surface Duct (Ref 1)

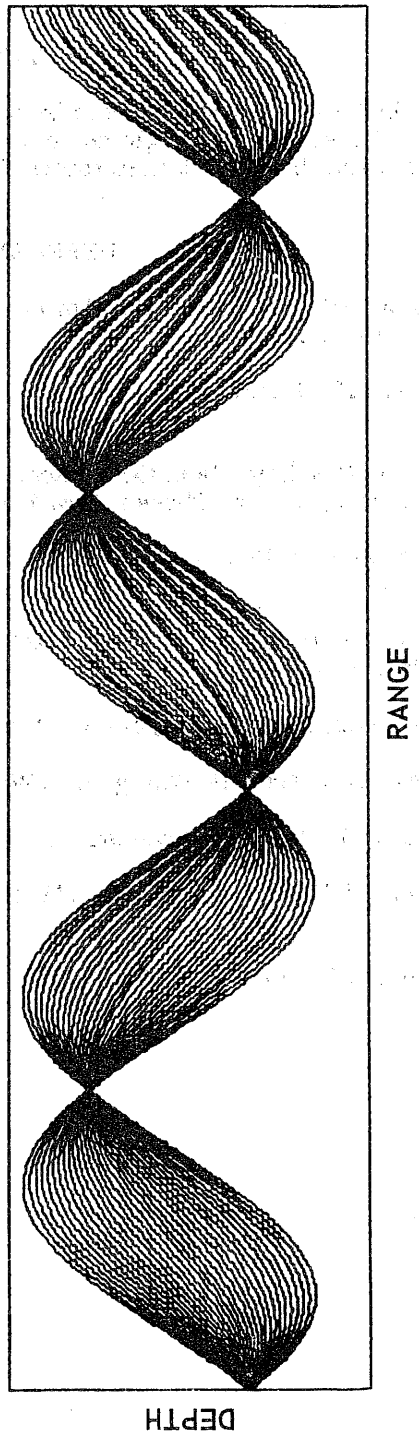

Figure 2 Ray Tracing in a Parabolic Duct (Ref 1)

INTRODUCTORY REVIEW

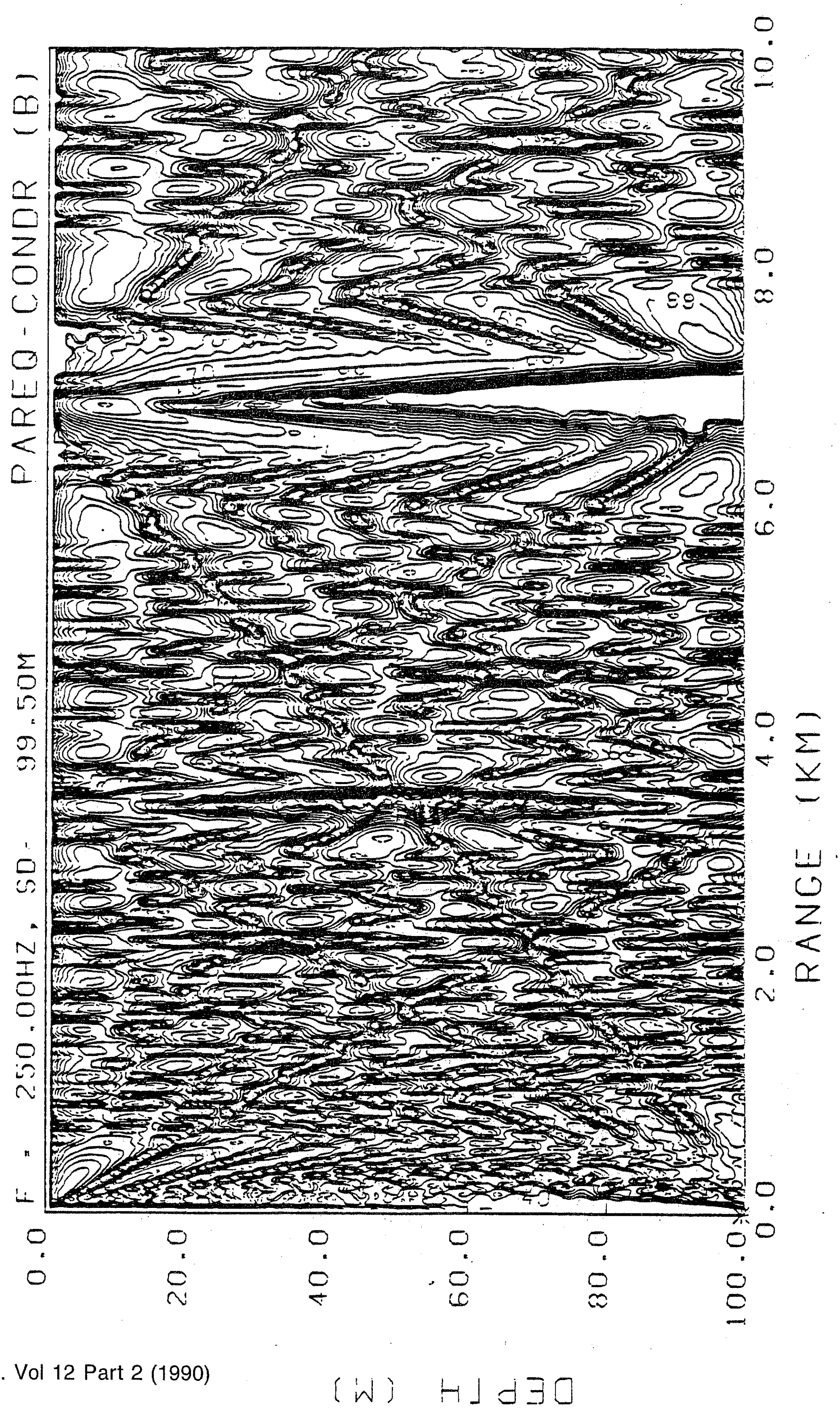

Figure 3 Transmission Loss Contours for Isovelocity Shallow Water

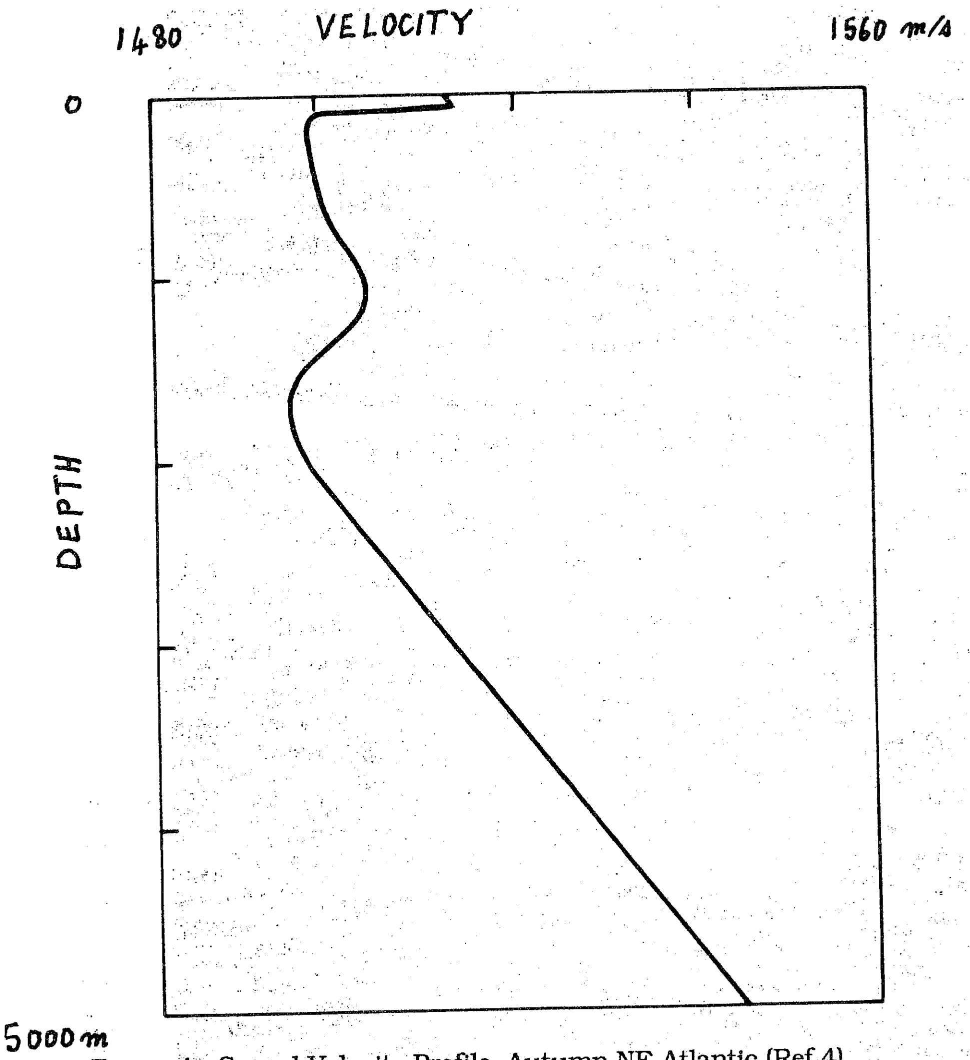

Figure 4 Sound Velocity Profile, Autumn NE Atlantic (Ref 4)

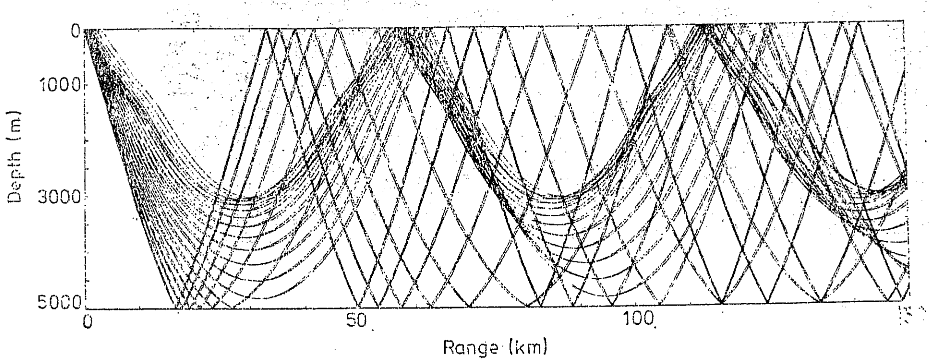

Figure 5 Ray Tracing for Whole Deep-Water Channel (Ref 4)

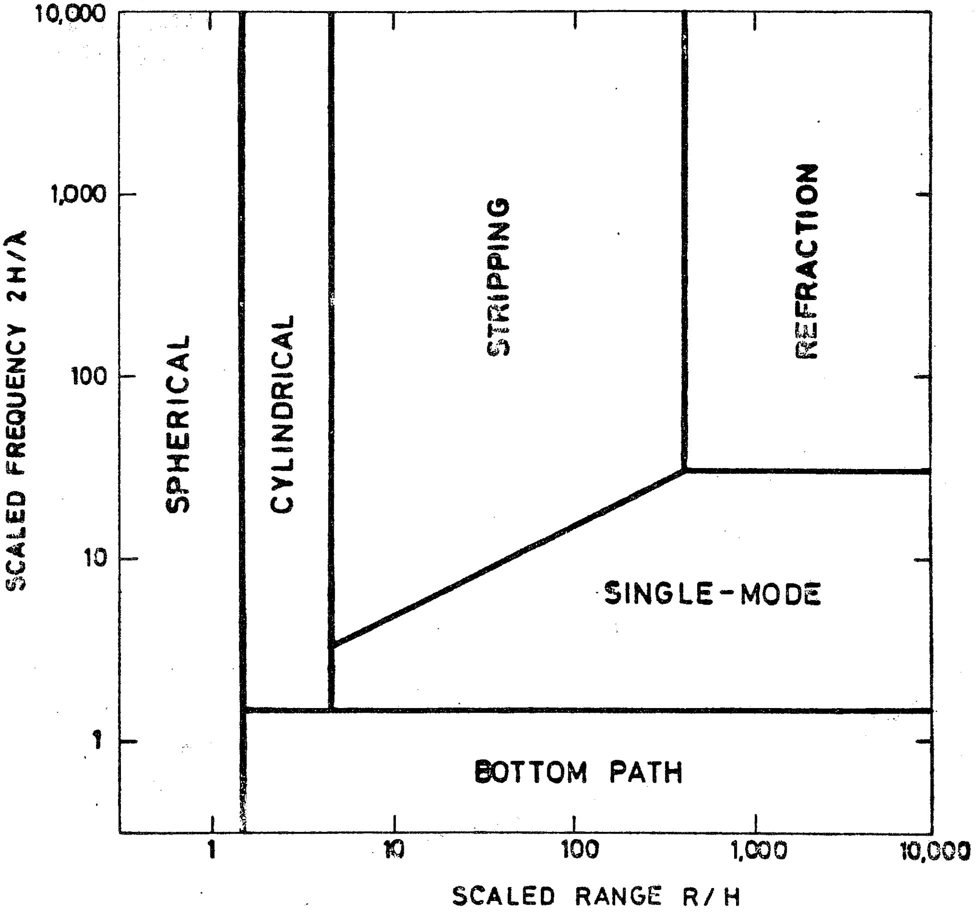

Figure 6 Propagation Regions for Shallow Water with Slight Layering

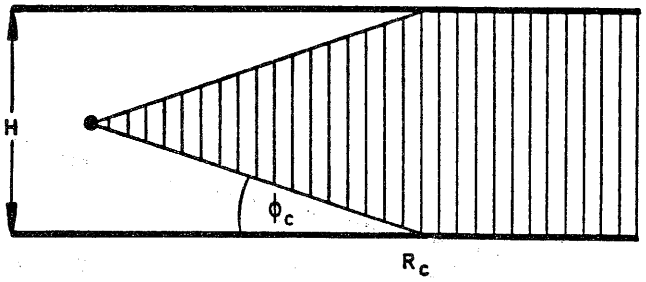

Figure 7 Cylindrical Spreading Region (Ref 9)

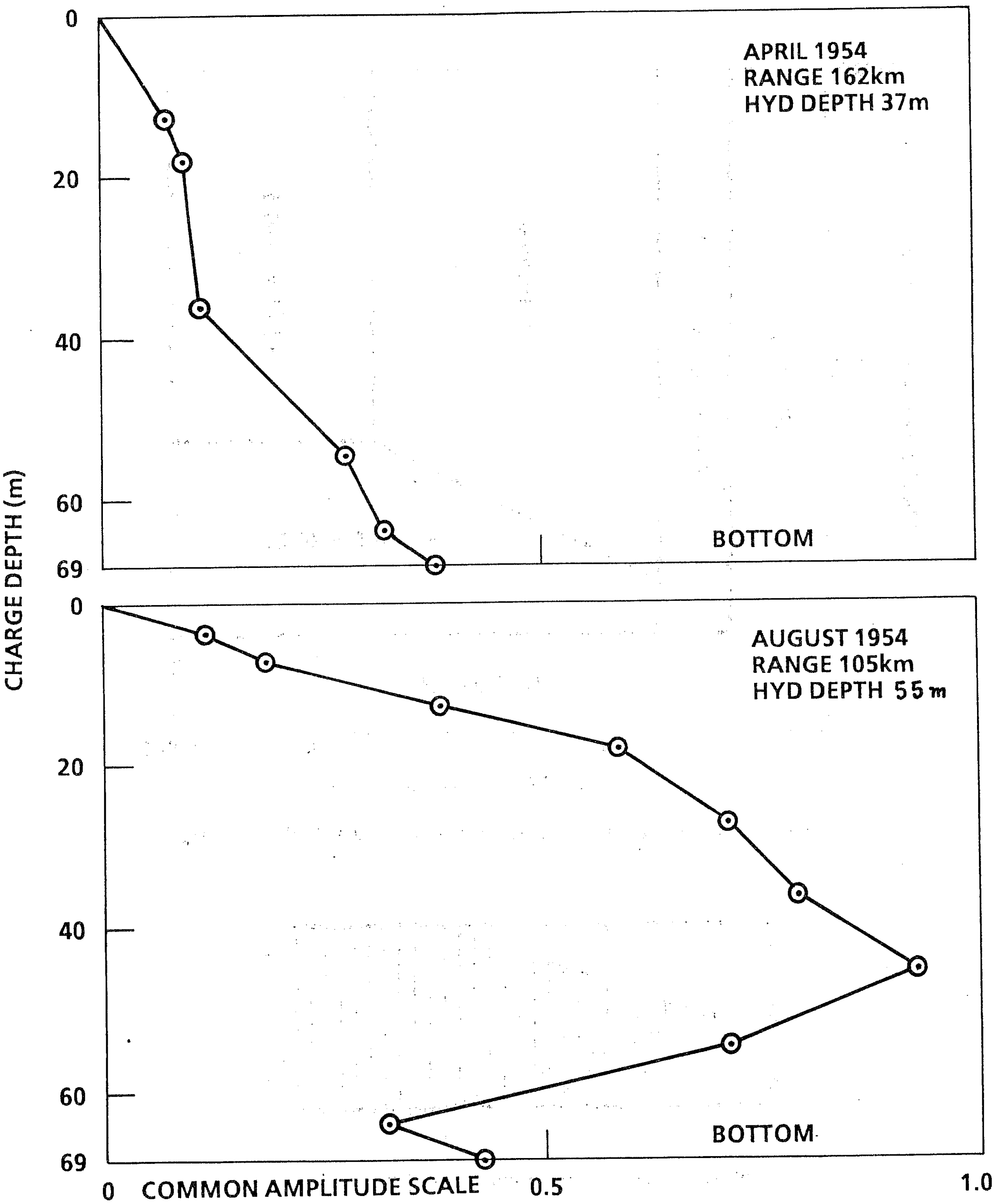

Figure 8 Depth Dependence at 35 Hz in the North Sea

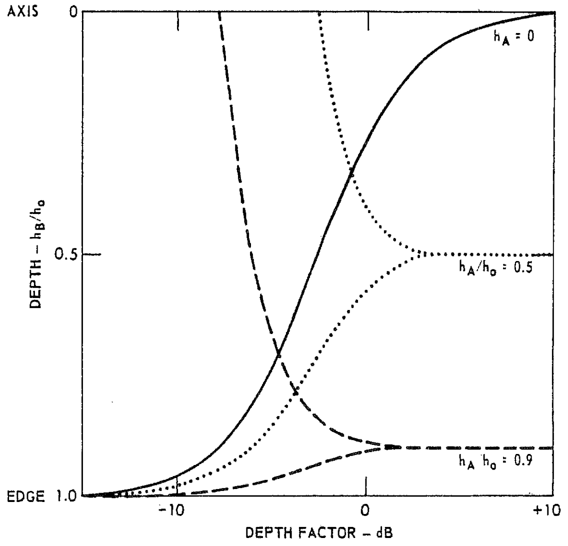

Figure 9 Depth Dependence of Level for a Surface Duct, as a Function of Source and Receiver Depths h_A and h_B

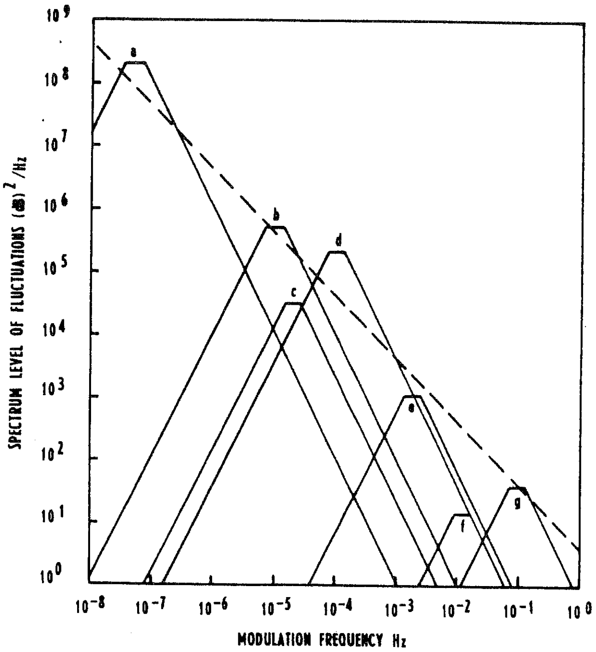

Figure 10 Fluctuation Spectra in Shallow Water
a Seasonal, b Diurnal, c Storms, d Tides, e Internal Waves,
f Local Fish, g Surface Waves